

Supercooling reduction in water-based PCMs using soya oil ester: thermal characterization and nucleation analysis

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Abstract

Water-based phase change materials (PCMs) are attractive for low-temperature thermal energy storage due to their high latent heat; however, their application is limited by severe supercooling caused by inefficient nucleation. This study evaluates the nucleation efficiency of soya oil ester as an additive for reducing supercooling of water-based PCMs. PCM samples were prepared with soya oil ester concentrations of 10%, 12.5%, 15%, and 17.5% by weight, each with a total mass of 100 g. Thermal characterization was performed using Differential Scanning Calorimetry (DSC) and the T-history method. DSC measurements were conducted in triplicate for each composition, while T-history tests employed parallel samples under identical cooling conditions. The temperature and enthalpy uncertainties of the DSC system were ± 0.1 °C and $\pm 2\%$, respectively, and the thermocouples used in the T-history setup exhibited an uncertainty of ± 0.5 °C. The results show a substantial improvement in nucleation efficiency, with supercooling reduced from 7.5 °C in pure water to 1.2, 0.8, 0.5, and 0.2 °C for ester concentrations of 10%, 12.5%, 15%, and 17.5%, corresponding to a suppression efficiency of up to 97.3%. The freezing onset temperature increased from -19.5 °C to -12.0 °C, indicating enhanced heterogeneous nucleation. Crystallization shifted from multi-step behavior in pure water to a single, reproducible event in modified PCMs. Although latent heat decreased slightly, it remained suitable for cold thermal energy storage. Overall, soya oil ester significantly improves nucleation performance and thermal reliability of water-based PCMs.

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INTRODUCTION

Phase change materials (PCMs) are widely utilized in thermal energy storage (TES) systems due to their ability to store and release large amounts of latent heat at nearly constant temperatures during phase transitions [1]. For low-temperature applications, including cold thermal storage, refrigeration, and food cold-chain systems, water-based PCMs are particularly attractive because of their high latent heat (~334 kJ/kg), abundance, low cost, and non-toxic nature [1][2]. However, their practical deployment is

significantly constrained by supercooling, where crystallization is delayed well below the equilibrium freezing point, resulting in unstable and delayed latent heat release [1].

Since 2021, considerable research has focused on understanding and mitigating supercooling in PCMs [1][3]. Various strategies have been reported, including the incorporation of heterogeneous nucleating agents, conductive or porous fillers, nanoparticles, microencapsulation, and nano-phase change emulsions [3, 4, 5].

Among these approaches, heterogeneous nucleation has consistently been identified as the most effective mechanism for suppressing supercooling and stabilizing phase transition behavior [1][3]. Nevertheless, many proposed solutions involve complex synthesis routes, nanoparticle additives, or encapsulation techniques that increase system cost and reduce scalability, particularly for simple water-based PCM systems [4][5].

In parallel, recent studies (2023 onward) have emphasized the development of bio-based PCMs and additives to improve sustainability and reduce reliance on petrochemical materials [2, 6, 7]. Vegetable oils, fatty acid esters, and related bio-derived compounds have demonstrated tunable thermal properties and potential nucleation activity [2]. Despite these advances, most investigations focus on non-aqueous systems or require extensive processing, while studies specifically addressing simple, bio-based additives capable of effectively suppressing supercooling in water-based PCMs remain limited.

Recent research (2024–2026) has further highlighted the need for quantitative evaluation of nucleation performance, including precise measurement of supercooling reduction, freezing onset shifts, and crystallization reproducibility [3, 8, 9]. Although advanced PCM systems have achieved substantial supercooling suppression, they often demand strict formulation control and additional manufacturing complexity [5, 9, 10]. From an engineering perspective, there remains a clear demand for a low-cost, scalable, and water-compatible solution that improves nucleation behavior without altering conventional TES system design.

Water, despite its superior latent heat capacity and environmental compatibility, is intrinsically limited by its fixed phase transition temperature (0 °C) and pronounced supercooling [11][12]. Recent findings suggest that incorporating small fractions of soy oil ester into water may significantly mitigate supercooling while modifying the effective freezing temperature [13]. Experimental results indicate that aqueous soy-oil-ester blends (10–17.5 wt%) can reduce supercooling from 7.5 K to as low as 0.2 K, as confirmed through Differential Scanning Calorimetry (DSC) and T-history analysis [13]. Additionally, the freezing point depression to approximately −12 °C extends the applicability of the bio-PCM to refrigeration and cold storage systems operating between −5 °C and −12 °C [14][15].

Despite these promising results, a systematic framework that links bio-based additive concentration, heterogeneous nucleation theory (Classical and Non-Classical), and reproducible multi-method thermal characterization remains underdeveloped. Therefore, this study investigates aqueous soy-oil-ester/water blends as a low-temperature bio-PCM and evaluates their nucleation behavior using both DSC and T-history methods. It is hypothesized that increasing ester concentration (10–17.5 wt%) will (i) significantly reduce supercooling, (ii) shift the freezing onset temperature toward higher values, and (iii) promote a more stable, single-step crystallization process. By validating these hypotheses experimentally, this work aims to provide a scalable and engineering-compatible strategy for enhancing the thermal reliability of water-based PCMs in low-temperature TES systems.

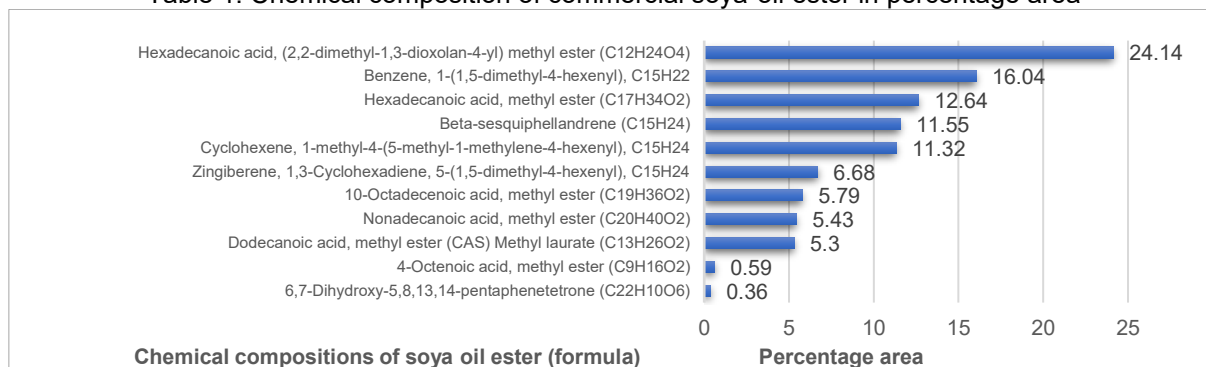
MATERIALS AND METHODOLOGY

Materials

This study used tap water and soybean oil ester as materials, combined into a single solution. Esterification of soybean oil produced fatty acid methyl esters (FAMEs), including methyl palmitate and oleate, confirming the product's soybean oil origin [16]. Soybean oil ester mainly consists of esters, in which an alkyl (-O) group replaces an acid's hydroxyl (-OH) group [8]. These polar esters partially ionize in water, releasing hydrogen ions (H⁺) and enhancing solubility. In aqueous preparations, the components primarily form dispersed droplets and/or interfacial layers, while minor polar constituents promote dispersion and interfacial contact that may influence heterogeneous nucleation.

Soya-oil esters were chosen as nucleating agents to minimize costs, a critical consideration for large-scale PCM applications. Unlike fatty acid esters, which necessitate expensive purification processes, soya-oil esters can be utilized without additional refinement, offering a cost-effective alternative. The chemical composition of soya-oil ester was determined using Gas Chromatography-Mass Spectrometry (GCMS). Solutions were prepared at various weight concentrations 10%, 12.5%, 15%, and 17.5%. For example, a 10% solution was prepared by dissolving 10 g of soya oil ester in 90 g of water, followed by stirring for 30 minutes to ensure homogeneity. The GCMS analysis, summarized in Table 1, revealed that soya-oil ester comprises primarily methyl esters (53.89%), along with benzene (16.4%), 1,3-cyclohexadiene (6.85%), beta-sesquiphellandrene (11.55%), and other minor components (11.68%).

Table 1. Chemical composition of commercial soya-oil ester in percentage area



Methodology

The research methodology was conducted in a sequential and controlled manner, as illustrated in the flowchart (Figure 1). First, water-based PCMs were prepared by mixing distilled water with 10-17.5 wt% soya oil ester under magnetic stirring for 30 minutes to ensure homogeneity. Second, 100 g PCM samples were fabricated at each concentration level and prepared in replicate sets to ensure statistical reliability. Third, thermal properties and phase transition behavior were characterized using Differential Scanning Calorimetry (DSC) under controlled heating and cooling conditions. Fourth, dynamic freezing behavior was evaluated using the T-history method, in which duplicate samples were cooled in a refrigerated bath at $-20\text{ }^{\circ}\text{C}$ and monitored using calibrated thermocouples. Fifth, supercooling degree, freezing onset temperature, and nucleation efficiency were quantitatively determined based on temperature-time data. Finally, measurement uncertainty was assessed to ensure data reliability and consistency across both DSC and T-history analyses.

The Differential Scanning Calorimetry (DSC) was prior instrument calibration following standard reference materials to ensure measurement accuracy. The temperature and enthalpy uncertainties of the DSC system were $\pm 0.1\text{ }^{\circ}\text{C}$ and $\pm 2\%$, respectively. While dynamic freezing behavior was further evaluated using the T-history method. Duplicate samples were cooled in a refrigerated bath maintained at $-20\text{ }^{\circ}\text{C}$, and temperature profiles were recorded using calibrated T-type thermocouples. Data acquisition uncertainty was minimized through sensor calibration and controlled environmental conditions, and the T-type thermocouples used in the T-history setup exhibited an uncertainty of $\pm 0.5\text{ }^{\circ}\text{C}$. Supercooling degree, freezing onset temperature, and nucleation efficiency were calculated from temperature-time curves.

Preparation of PCM samples

PCM solution was developed with tap water as the continuous phase and soya-oil ester as the dispersed phase, designed to achieve energy conservation at sub-zero temperatures. The solutions were prepared in selected mass fractions to lower the water's phase change temperature.

Samples with varying concentrations (10%, 12.5%, 15%, and 17.5% by weight) were prepared, each weighing 100 g. The preparation involved mixing the components under molten conditions and storing them at room temperature for one hour. A semi-analytical digital balance with an accuracy of $\pm 0.0001\text{ g}$ was used to ensure precise weight measurements of the samples.

DSC (Differential Scanning Calorimetry)

Thermal characteristics, i.e., melting or solidifying temperatures and latent heat, are the primary focus of TES systems. This process is typically measured by Differential Scanning Calorimetry (DSC), one of the most commonly used techniques for thermal characterization of physicochemical transformations. DSC is widely used for analyzing thermodynamic data due to its ease of providing substantial information. This examination can provide qualitative and quantitative evidence about the sample's phase transitions, including transition temperature, enthalpy, heat capacity, specific heat, and latent heat. PerkinElmer® DSC 8000 was used to determine the thermal characteristics of the samples. First, the samples were put in a sealed aluminum crucible pan. Each of the samples was prepared to be 10 ml (10 cc). Then, the samples were analyzed under a heating rate of $5\text{ }^{\circ}\text{C}/\text{min}$ (heating rate) (for heating and cooling) using a constant stream of Nitrogen (N_2) gas. The flow rate of N_2 is set at 20 ml/min at a temperature scale of $25\text{ }^{\circ}\text{C}$ to $-100\text{ }^{\circ}\text{C}$.

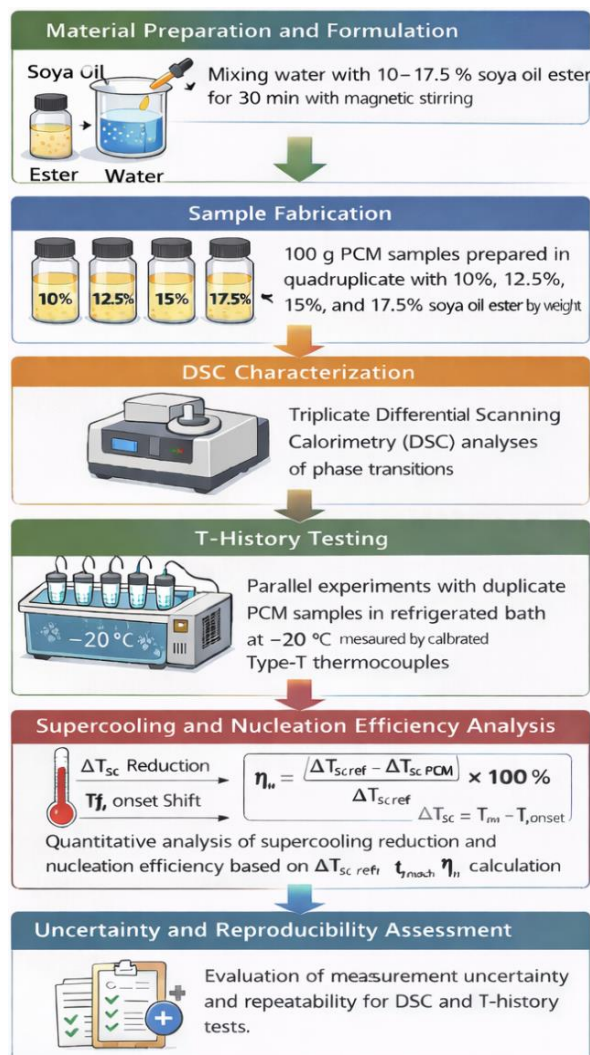


Figure 1. Research method flowchart

The device has significant deviation in enthalpy and temperature reached $\pm 2\%$ and ± 0.1 °C, respectively. To weight the samples of DSC test, a semi-analytical digital balance (accuracy ± 0.00001 g) was employed. The melting/nucleation characteristics are reported using the onset point of a DSC curve, as it is less dependent on the heating/cooling rate. The onset point of a DSC curve is defined by the intersection of the tangent at the point of maximum slope on the peak and the extrapolated sample baseline.

T-history method

The T-history method, a widely used approach in thermal analysis, has become a crucial tool for researchers studying PCM due to its reliable and accurate characterization of their thermal properties. The freezing and melting characteristics of the PCM samples were assessed using the T-history method, an approach whose principle is based on recording

temperature-time curves. Combined with the DSC test, the T-history method enhanced the accuracy of determining the PCM enthalpy curve. This approach is critical because the basic material properties may differ from those of the investigated samples. Figure 2 illustrates the experimental setup for obtaining the T-history of the PCM candidate. The PCM samples are placed in a glass tube and submerged in a water bath. The cooling medium of water bath is a mixture of 60% water and 40% polypropylene glycol (by volume). The pump circulates the cooling medium, which is cooled to a specific temperature using vapor compression refrigeration. A minimum temperature of -25 °C was achievable for the cooling medium.

In T-history test, the cooling medium's temperature was maintained at a stable -20 °C using a PID thermostat that had a precision of ± 0.2 °C.

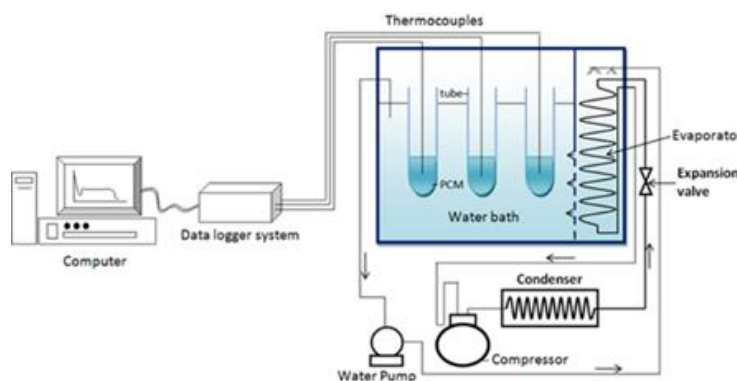


Figure 2. Schematic diagram for the T-history method

Data-scan 7000 data acquisition hardware coupling with 7320 and 7020 expansion modules from Measuring Systems Ltd were used to display and store the measurement result on a PC. Each module consists of 16 input channels of thermocouples. Type T thermocouples, with an error of ± 0.5 °C, were installed to determine the PCM samples' temperature and cooling medium's temperature. The thermocouple was calibrated using a water bath calibration with the uncertainty ± 0.05 °C.

To improve cross-study comparability, the degree of supercooling (ΔT_{sc}) was defined consistently as the difference between the melting onset temperature and the nucleation/freezing onset temperature determined from the DSC thermogram; for T-history, ΔT_{sc} was determined from the temperature-time curve as the difference between the apparent equilibrium freezing plateau (after recalescence) and the minimum temperature reached immediately prior to the onset of crystallization.

RESULTS AND DISCUSSION

Thermal Analysis of Tap Water

Figure 3 shows the DSC curve for tap water intended to grasp a meaningful comparison of the thermal properties and behavior associated with PCM candidates' melting and freezing processes. It will also provide a basis analysis for the DSC curve from PCM candidates. The thermal analysis of tap water using DSC revealed distinct characteristics of its phase change processes.

The DSC curve for tap water exhibited two prominent exothermic peaks during the freezing process: the first at approximately -20 °C and the second at -26.03 °C. These peaks suggest a multi-step freezing process involving two different crystallization morphologies. The first peak, attributed to eutectic impurities in the water, likely results from dissolved minerals and salts such as chloride ions, fluoride, and calcium carbonate. These impurities act as natural nucleating agents, facilitating heterogeneous nucleation during the initial crystallization stage [9].

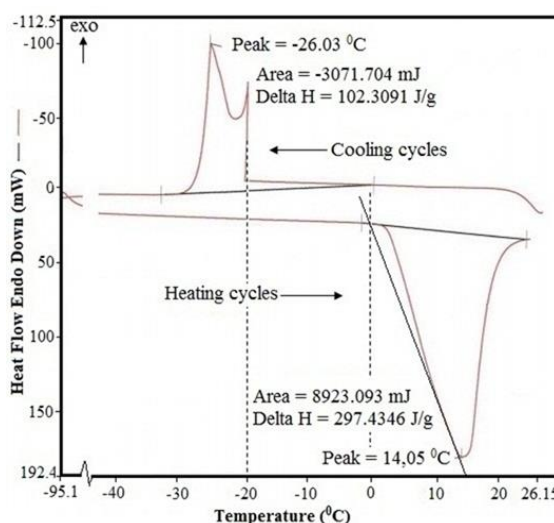


Figure 3. DSC thermogram of tap water during heating and cooling

DSC for Soya Oil Ester-Water Mixtures

The DSC analysis of water modified with varying concentrations of soya oil ester (10%, 12.5%, 15%, and 17.5% by weight) demonstrated significant improvements in thermal properties.

As shown in Figure 4–Figure 7, adding soya oil ester eliminated the separation of peaks observed in the thermogram of pure tap water. This elimination indicates a uniform freezing and melting process in the modified water. Specifically, Figure 4 (10%) and Figure 5 (12.5%) show progressive narrowing toward a single dominant freezing peak, while Figure 6 (15%) and Figure 7 (17.5%) show further stabilization of the freezing event with reduced peak splitting.

The degree of supercooling decreased as the concentration of soya oil ester increased. For instance, the supercooling degree was reduced to 1.2 °C at 10% concentration, 0.8 °C at 12.5%, 0.5 °C at 15%, and 0.2 °C at 17.5% concentration. This reduction reflects the role of soya oil ester as a nucleating agent, promoting faster and more efficient ice nucleation during freezing [9].

The melting points of the soya oil ester-water mixtures were significantly lower than that of pure water. Table 2 summarizes the melting and freezing points for different concentrations. The melting temperature ranged from -6.5 °C to -12 °C, depending on the concentration, with latent heat values varying between 145.81 J/g and 208.81 J/g during melting and between 94.65 J/g and 120.23 J/g during freezing.

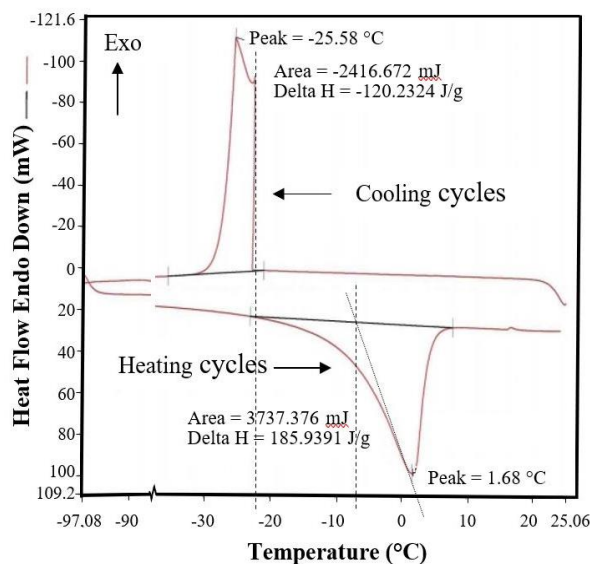


Figure 4. DSC thermograms of 10% soya-oil ester/water blend (heating/cooling)

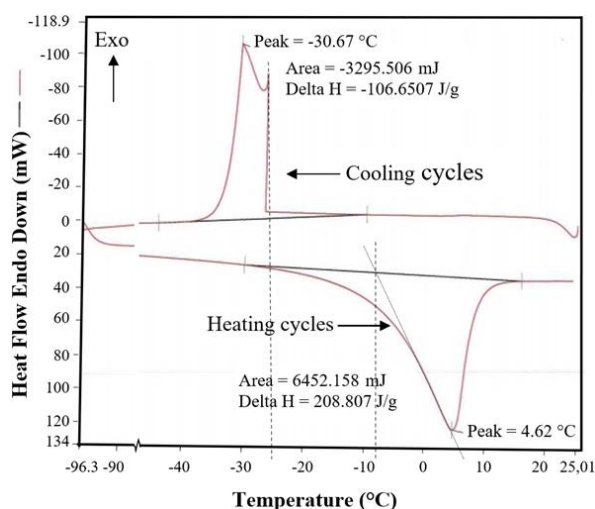


Figure 5. DSC thermograms of 12.5 % soya-oil ester/water blend (heating/cooling)

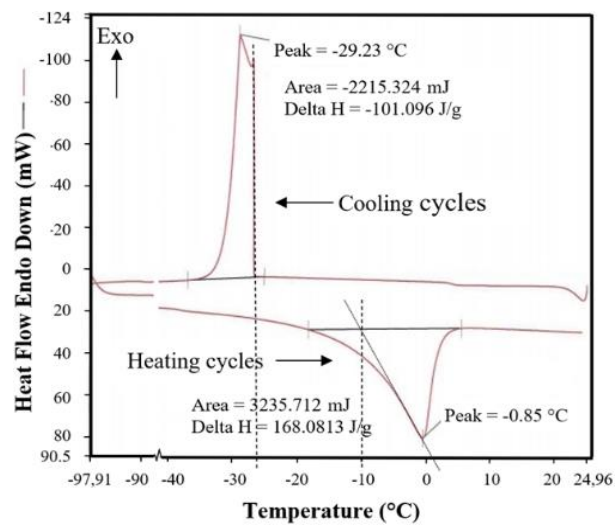


Figure 6. DSC thermograms of 15% soya-oil ester/water blend (heating/cooling)

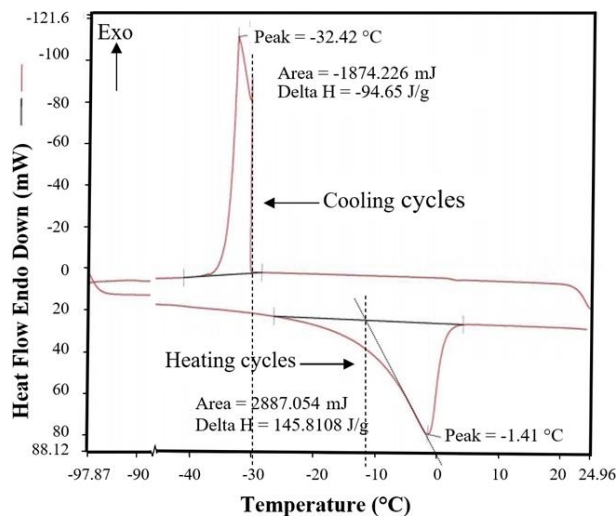


Figure 7. DSC thermograms of 17.5% soya-oil ester/water blend (heating/cooling)

Table 2. Thermal properties of soya oil ester-water mixtures

Samples (Vol. %)	DSC				T-history	
	Heating process		Cooling process		Cooling process	
	Melting Temp. (T_m , °C)	Latent heat of melting (ΔH_m , J/g)	Freezing Temp. (T_f , °C)	Latent heat of freezing (ΔH_f , J/g)	Freezing Temp. (T_f , °C)	Super- cooling degree (K)
Tap water	0	297.4346	-19.5	-102.3901	0	7.5
10/90 (s/w)	-7	185.9391	-22	-120.2324	-6.5	1.2
12.5/87.5 (s/w)	-8.5	208.807	-25	-106.6507	-8	0.8
15/85 (s/w)	-10	168.0813	-26.5	-101.096	-9.5	0.5
17.5/82.5 (s/w)	-12	145.8108	-29.8	-94.65	-12	0.2

s/w = Soya-oil ester in water

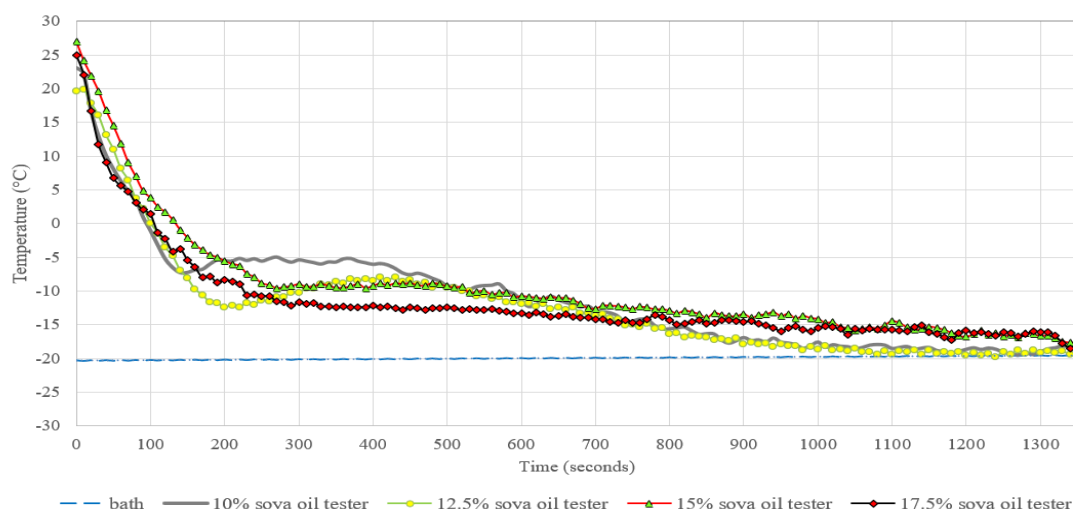


Figure 8. Temperature profiles of Soya Oil Ester-Water PCM at different concentrations

T-History Results

The T-history experiments supported the DSC findings by demonstrating the enhanced thermal behavior of the soya oil ester-water PCM. Figure 8 illustrates the cooling profiles for water mixed with 10%, 12.5%, 15%, and 17.5% soya oil ester concentrations. The freezing points of the modified PCM decreased progressively with higher ester concentrations, reaching -6.5 °C, -8.0 °C, -9.5 °C, and -12.0 °C, respectively. The curves show earlier onset of crystallization (reduced supercooling) and faster recalescence/plateau formation as ester concentration increases, consistent with enhanced heterogeneous nucleation. The reduction in freezing point aligns with the concept of freezing-point depression in multicomponent aqueous systems [13].

DISCUSSION

Mechanisms of Supercooling Reduction

Supercooling in tap water arises from the absence of nucleating agents, which delays the phase transition. The results of this study highlight the efficacy of soya oil ester as a heterogeneous nucleating agent. Its incorporation into water promotes the aggregation of water molecules into ice-like structures at higher temperatures, reducing the kinetic barrier to crystallization. The polar components of soya oil ester molecules facilitate this nucleation process by enhancing intermolecular interactions, thereby minimizing supercooling [9][17].

Nucleation-theory interpretation (CNT and NCNT)

Nucleation is the critical initial step in water freezing and governs supercooling, phase stability, and ice formation kinetics in PCMs.

Under Classical Nucleation Theory (CNT), ice nuclei form stochastically in a metastable supercooled liquid and grow only after reaching a critical size; the nucleation barrier depends on interfacial free energy, temperature undercooling, and the availability of heterogeneous substrates. Recent work bridging CNT with simulation highlights how interfacial properties control homogeneous and heterogeneous nucleation rates [17, 18, 19].

In the present system, the dispersed soy-oil-ester phase can provide interfacial sites that reduce the effective nucleation barrier and increase nucleation probability, consistent with the observed reduction in ΔT_{sc} and the transition from multi-step to more uniform crystallization. Non-Classical Nucleation Theory (NCNT) further suggests that intermediate pre-nucleation structures may precede ordered ice formation; recent experimental and modeling studies support the existence of such intermediate stages during freezing of supercooled water [18, 19, 20]. While this study does not directly measure nucleation rates or interfacial free energy, the DSC/T-history trends are consistent with nucleation-barrier reduction via additive-enabled heterogeneous nucleation.

Influence of Concentration on Thermal Properties

The thermal performance of soya oil ester-water PCM was found to be concentration-dependent. Higher concentrations of soya oil ester improved the uniformity and efficiency of the phase transition, as evidenced by the bell-shaped thermal curves in the DSC results. This result indicates a shift from multi-step crystallization in

pure water to a single-step, efficient freezing process in the modified PCM [9][17].

The observed decrease in latent heat with increasing soya oil ester concentration suggests a trade-off between reducing supercooling and maintaining high energy storage density. While the highest ester concentration (17.5%) achieved the lowest supercooling degree (0.2 °C), it also had the lowest latent heat of melting and freezing. This trade-off must be carefully balanced in practical applications, depending on the specific requirements of the TES system.

Practical Implications for TES Applications

This research adds to the growing knowledge of bio-based PCM, particularly in improving their performance for low-temperature applications. The results align with previous studies highlighting the potential of fatty acid esters, including soya oil esters, as effective nucleating agents and thermal energy storage materials. Additionally, the findings support the increasing focus on sustainability and environmental impact in TES technologies, aligning with global efforts to reduce reliance on non-renewable resources and lower carbon footprints.

Comparison with Literature and Future Directions.

The results of this study corroborate findings from previous research on bio-based PCM. Studies have shown that fatty acid esters, including soya oil ester, effectively lower the freezing point and enhance nucleation in PCM [5][10]. Furthermore, the role of impurities in facilitating heterogeneous nucleation aligns with observations made in similar investigations of water-based PCM [9, 21, 22].

This study also contributes to the ongoing efforts to replace conventional petrochemical-based PCM with more environmentally friendly alternatives by utilizing renewable, bio-based materials such as soya oil ester. The reduction in supercooling and the ability to fine-tune the phase transition temperatures make soya oil ester-water PCM attractive for applications requiring stable and reliable thermal energy storage. Additionally, exploring composite formulations that combine soya oil ester with other bio-sourced additives may further enhance their thermal conductivity and energy storage capacity. Life cycle assessments are also needed to quantify the environmental benefits of these bio-based PCM relative to conventional options [3, 9, 23].

Recent water-based cold-TES PCMs report multiple approaches to reduce supercooling, including stabilizing aqueous PCMs with benign additives (e.g., glycine-water systems) and improving stability for cold-chain logistics [22], as well as developing novel water-based composite PCMs for cold energy storage [21]. In parallel, supercooling suppression in other PCM classes has been achieved using engineered nucleators such as nanoparticles (e.g., ZnO-enhanced polyols) [24] and nano-emulsion strategies (e.g., paraffin nano-PCMs with particle-assisted nucleation [25]. Salt-hydrate systems (e.g., $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$) also continue to require formulation strategies to mitigate supercooling for long-term recovery [26]. Compared with these approaches, the present soy-oil-ester/water bio-PCM achieves near-elimination of supercooling (down to ~ 0.2 °C) in a simple, bio-derived formulation while shifting the phase-change range into the refrigeration-relevant window, suggesting a complementary, sustainability-oriented pathway for nucleation control in cold-TES.

Limitations and Future Work

The present soy-oil-ester/water formulation is designed for cold-TES operation in the approximate -5 to -12 °C range; performance outside this window, under different cooling/heating rates, or in the presence of strong thermal gradients may differ. The reported thermal behavior was obtained for soy-oil-ester mass fractions of 10-17.5 wt% under specific measurement conditions (DSC at 5 °C min⁻¹; T-history at a -20 °C bath), and thus extrapolation beyond these ranges should be made cautiously. Because ice nucleation is intrinsically stochastic and sensitive to sample history, container surface condition, and impurities, this study does not yet provide statistical quantification of run-to-run variability; replicate tests and uncertainty reporting for ΔT_{sc} and transition temperatures are therefore needed. In addition, the ester phase is dispersed in water, so long-term dispersion stability, possible phase separation, and sensitivity to water chemistry (e.g., tap vs deionized) remain to be evaluated. Finally, device-level implementation may be constrained by heat-transfer limits (low effective thermal conductivity and reduced power density) and by practical containment needs to prevent leakage during melting, where encapsulation or form-stable matrices may introduce added thermal resistance and cost.

Future studies should adopt standardized protocols for reporting supercooling and nucleation metrics (ΔT_{sc} definitions, cooling rate,

sample geometry, surface/impurity conditions, and cycle-to-cycle variability) to enable cross-study comparison. Mechanistic, model-guided design grounded in CNT/NCNT should be pursued to link ester composition and interfacial-layer characteristics to nucleation probability and supercooling magnitude, supported by targeted surface characterization and, where feasible, molecular simulation. Application-relevant durability testing should be extended to long-horizon freeze–thaw cycling across realistic operating profiles to quantify kinetics, hysteresis, phase segregation, and drift in nucleation behavior.

Disadvantages and mitigation strategies

A central limitation of the soy-oil-ester/water system is the intrinsic trade-off between suppressing supercooling and preserving gravimetric latent heat as ester fraction increases. This can be addressed by selecting an application-specific optimum composition (minimizing ΔT_{sc} while maintaining adequate latent heat) and, where needed, pairing the ester with low loadings of benign nucleators or structuring agents that enhance nucleation without substantial dilution. A second challenge is dispersion stability over storage and repeated cycling; mitigation may rely on food-safe emulsifiers, hydrogel/bio-matrix stabilization, or encapsulation/form-stable architectures to prevent phase separation.

Future development and anticipated difficulties

Future work should advance this bio-PCM from proof-of-concept toward deployable cold-TES by (i) building mechanism-informed, predictive nucleation models that link ester composition and interfacial characteristics to nucleation probability and ΔT_{sc} , (ii) demonstrating long-horizon cycling stability under refrigeration-relevant operating profiles, and (iii) scaling the formulation into device-level modules for cold-chain packaging and refrigeration load shifting.

Key challenges are expected in quantifying nucleation rates and interfacial free energies within CNT/NCNT frameworks while disentangling freezing-point depression from heterogeneous nucleation together with establishing standardized protocols that control sample history, container surface effects, and impurity levels. Experimentally, maintaining dispersion stability over many cycles and characterizing droplet/interfacial features remain nontrivial, particularly if stabilization strategies (encapsulation or matrices) introduce added thermal resistance.

CONCLUSION

This study demonstrates that soya oil ester is an effective bio-based additive for suppressing supercooling in water-based phase change materials (PCMs) intended for low-temperature thermal energy storage. Experimental results obtained from Differential Scanning Calorimetry (DSC) and the T-history method show that the supercooling degree of pure water (7.5 °C) was progressively reduced to 1.2 °C, 0.8 °C, 0.5 °C, and 0.2 °C with the addition of 10%, 12.5%, 15%, and 17.5% soya oil ester by weight, respectively, corresponding to a nucleation efficiency exceeding 90% at higher concentrations. The ester-modified PCMs exhibited a more stable and reproducible crystallization behavior, characterized by a single freezing event and reduced variability in freezing onset temperature, indicating improved thermal reliability compared to pure water. Although an increase in ester concentration resulted in a gradual decrease in latent heat, the measured values remained suitable for cold thermal energy storage applications, representing an acceptable trade-off between energy storage capacity and nucleation stability. Overall, the findings confirm that the incorporation of soya oil ester provides a simple, low-cost, and practical approach to mitigating supercooling in water-based PCMs without requiring complex material processing, making it a promising solution for engineering-oriented cold energy storage systems.

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